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APPARATUS AND METHOD FOR FUSION REACTOR

Cross-reference to Related Applications

[0001] This application claims priority from United States Patent Application No. 60/363,401 filed 12 March 2002.

Technical Field

[0002] This invention relates to nuclear fusion. Specific embodiments of the invention relate to nuclear fusion reactors and methods for generating energy by promoting nuclear fusion.

Background

[0003] Nuclear fusion reactions between atomic nuclei can produce large amounts of energy. Fusion reactions involve bringing together atomic nuclei against their mutual electrostatic repulsion and fusing pairs of nuclei together to make heavier nuclei. Energy is released in this process. Isotopes of light elements (i.e. elements having a relatively small number of protons) are the easiest to fuse, because the electrostatic repulsion between the nuclei of light elements is smaller than that of heavier elements.

[0004] Fusion reactions involving the nuclei of such light elements could be used to produce energy with significantly reduced radioactivity than comparable fission reactions. The easiest fusion reactions to produce include:

(i) $D + D => {}^3He + n + 3.6$ MeV;

(ii) $D + T => {}^4He + n + 17.6$ MeV; and

(iii) $D + {}^3He => {}^4He + H + 18.3$ MeV

where n is a neutron, H is a hydrogen atom having a single proton, D is deuterium (i.e. a hydrogen isotope with 1 proton and 1 neutron), T is tritium (i.e. a hydrogen isotope with 1 proton and 2 neutrons), and ${}^xHe$ is a helium ion having x neutrons and protons. The number of MeV is the energy released by the fusion reaction.

[0005] Inducing nuclear fusion reactions is difficult, because of the energies required to accelerate the nuclei to speeds fast enough to overcome their mutual electrostatic repulsion and because the nuclei are so small that the chance that two passing nuclei will interact with one another in a manner which results in fusion of the nuclei is small.

[0006] The energy efficiency of a reactor is the ratio of the energy output to the energy input. In a fusion reactor, the energy output is largely determined by the number of fusion reactions that are induced in the reactor and the amount of capturable energy released. The energy input in a fusion reaction is largely determined by the amount of energy required to accelerate the nuclear reactants to thermonuclear speed and to confine the nuclear reactants in a space that allows them to interact.

[0007] In order to make a fusion reactor commercially viable, the energy output must be sufficient to offset the financial cost of manufacturing, installing and operating the reactor. The inventor is unaware of any nuclear fusion method or nuclear fusion reactor which can successfully produce energy in a controlled, reproducible and commercially viable manner.

[0008] One method for achieving controlled nuclear fusion involves heating a plasma of light nuclei to such a temperature that the thermal speed of the particles in the plasma is sufficient to produce fusion reactions between the nuclei. The plasma may be made of a deuterium-tritium mixture, for example. Containing the heated plasma while producing a sufficient number of fusion reactions to provide a commercially viable reactor has so far presented insurmountable difficulties.

[0009] Various means have been proposed to contain the plasma. Such proposals include the use of intense magnetic fields in a variety of configurations. Specific drawbacks with magnetic containment systems include: limited magnetic field strength; energy loss from plasma instabilities, heat losses and particle drift across the magnetic fields; and difficulties related to pumping sufficient amounts of energy into the plasma.

[0010] Inertial confinement techniques for implementing fusion reactors, involve quickly heating a solid pellet of fusionable material with one or more energy beams and letting the pellet explode, so that a sufficient number of fusion reactions occur before the temperature drops. Most inertial confinement experiments have been conducted using laser beams to heat the fusionable material, but ion beams and electron beams have also been proposed. A number of expensive apparatus have been developed to produce nuclear fusion reactions via inertial confinement techniques. The principal drawbacks of inertial confinement relate to costs and technological difficulties associated with generating the high-power beams used to heat the fusionable pellet. Although improvements have been made to inertial confinement devices, the inventor is currently unaware of any commercially viable inertial confinement power generation devices. No such devices have been able to produce power at a price competitive with other power sources.

[0011] Another technique proposed for producing fusion reactions involves providing a gaseous bubble of fusionable material in a liquid and then collapsing the bubble by creating an acoustic wave (i.e. a pressure wave) in the liquid. It has been suggested that upon the collapse of a bubble, fusionable material within the bubble can be compressed and heated to thermonuclear conditions (i.e. the fusionable nuclei are accelerated to sufficient speeds such that fusion reactions may occur). In

Science, March 2002, "Evidence for Nuclear Emissions During Acoustic Cavitation", Taleyarkhan et al. have proposed a basic apparatus for inducing nuclear fusion by bubble compression and claim to have detected neutrons and tritium produced during the collapse of bubbles of fusionable gas. The teachings of Taleyarkhan et al. are hereby incorporated by reference.

[0012] Flynn (U.S. Patent No. 4,333,796), Putterman et al. (U.S. Patent No. 5,659,173) and Pless (U.S. Patent No. 5,968,323) have proposed techniques for collapsing gaseous bubbles of fusionable material using substantially sinusoidal acoustic waves produced by ultrasound generators.

[0013] Sinusoidal acoustic waves have periods of relatively high pressure (i.e. during the peaks of the sinusoidal pressure waves) and periods of relatively low pressure (i.e. during the troughs of the sinusoidal pressure waves). A liquid in tension will cavitate. Because of cavitation, the pressure in a liquid can not be reduced significantly below zero, even during the troughs of an applied sinusoidal acoustic wave. For this reason, the peak pressure achievable using a sinusoidal acoustic wave is limited to approximately twice the static pressure of the liquid. The static pressure of the liquid is limited by the strength of the vessel used to contain the liquid.

[0014] There exists a need for apparatus and methods for nuclear fusion reactors that ameliorate at least some of the aforementioned disadvantages of the prior art.

Summary of the Invention

[0015] In accordance with the invention, a method for inducing nuclear fusion is disclosed. The method comprises: positioning a bubble

containing atomic nuclei at a location within a liquid filled vessel; generating a positive acoustic pulse in the liquid which surrounds and converges toward the bubble; and, allowing the acoustic pulse to compress the bubble to provide energy to the atomic nuclei and to thereby induce nuclear fusion therebetween.

[0016] In another aspect of the invention a nuclear fusion reactor is disclosed. The reactor comprises a vessel filled with liquid and a plurality of pistons positioned outside of the vessel. The pistons are actuable to strike an outer surface of the vessel and to thereby generate a positive acoustic pulse in the liquid. A bubble containing atomic nuclei is positionable at a location within the vessel, such that the acoustic pulse surrounds and converges toward the bubble to compress the bubble. Compression of the bubble provides energy to the atomic nuclei and thereby induces nuclear fusion therebetween.

[0017] Further features and applications of the invention are described below.

<u>Brief Description of the Drawings</u>

[0018] In drawings which depict non-limiting embodiments of the invention:

Figure 1 is cross-sectional view of a spherical nuclear fusion reactor according to a particular embodiment of the invention;

Figure 2 is a cross-sectional view of a spherical nuclear fusion reactor according to a second embodiment of the invention;

Figure 3 is a diagram showing the radial distribution of pressure in an acoustic pulse provided in accordance with the invention;

Figure 4 schematically depicts a piston control system used to control the movement of a piston in the Figure 2 reactor; and

Figure 5 schematically depicts a bubble tracking system and a bubble positioning system which may be used in the reactors of Figures 1 and 2.

Detailed Description

[0019] Throughout the following description, specific details are set forth in order to provide a more thorough understanding of the invention. However, the invention may be practiced without these particulars. In other instances, well known elements have not been shown or described in detail to avoid unnecessarily obscuring the invention. Accordingly, the specification and drawings are to be regarded in an illustrative, rather than a restrictive, sense.

[0020] This invention provides methods and apparatus which implement a "bubble compression" fusion reactor. The invention involves creating a spherically symmetric positive acoustic pulse in a liquid which contains a spherical bubble of fusionable material. The acoustic pulse compresses and collapses the bubble to correspondingly increase the pressure and temperature of the fusionable material contained therein. At the surface of the bubble, the peak pressure of the acoustic pulse is significantly greater than that achievable using a sinusoidal or other continuously oscillating acoustic waveform. Consequently, the temperature and pressure imparted on the fusionable material is greater. This facilitates nuclear fusion reactions in the compressed fusionable material within the collapsing bubble.

[0021] Figure 1 depicts a nuclear fusion reactor **10A** in accordance with a particular embodiment of the invention. Reactor **10A** includes a spherical vessel **12** filled with a liquid **14**. Spherical vessel **12** may generally be of any size. In a particular preferred embodiment, the

diameter of spherical vessel **12** is in the range of about 0.6m to about 2m and may be approximately 1m.

[0022] Liquid **14** may comprise any of a variety of substances that provide desirable characteristics, such as acoustic wave transfer speed, relatively low melting point, low vapour pressure at temperatures at or above the melting point of the liquid, and relatively high thermal conductivity and capacity. Liquid **14** may comprise a molten metal such as molten lithium or molten sodium, for example. As explained in greater detail below, lithium has the added advantage that it may react with neutrons produced in the fusion reaction to generate tritium which may be reused as a fusionable material. Further, lithium has a reasonably high cross-section for absorbing energy from neutrons and can serve as a shielding medium and also as a medium for converting energy of neutrons produced by fusion into heat.

[0023] Liquid **14** may contain one or more additives. The additives may include:

- Isotopes which can interact within a neutron released by a fusion reaction to yield two or more lower energy neutrons. A particular example of such an isotope is ^{11}B. Those skilled in the art will appreciate that other neutron multiplying isotopes may be used;
- Isotopes which absorb neutrons. The addition of such isotopes provides better shielding for the walls of reactor **10A**; and,
- Additives which increase a density of liquid **14** to provide a better match of acoustic impedance at the interface between liquid **14** and the wall of reactor **10A**.

[0024] As shown in Figure 1, reactor **10A** may include a pressure control system **16**. Pressure control system **16** functions to maintain liquid **14** at a suitable operating pressure. Pressure control system **16**

may comprise any of a wide variety of pneumatic and/or hydraulic elements. In the illustrated embodiment, pressure control system **16** comprises a piston **18** driven by a solenoid **20**. Solenoid **20** is preferably controlled by controller **116**. Controller **116** may comprise one or more suitably programmed computers or other data processors. Controller **116** may also comprise one or more analog electronic circuits configured to perform the functions described herein. Controller **116** controls solenoid **20** to maintain a hydrostatic pressure within reactor **10A** at a desired level. Pressure control system **16** may also comprise a pressure sensor (not shown) which provides a pressure feedback signal to controller **116**. The pressure at which liquid **14** is maintained may vary between specific embodiments of the invention. When liquid **14** comprises lithium, a suitable pressure may be in the range of 70 bar to 200 bar and may be approximately 100 bar to 125 bar, for example.

[0025] Within practical limits, maintaining liquid **14** at a higher pressure is desirable, since higher pressure reduces the sizes of bubbles of fusionable material and therefore both increases the initial density of the bubbles and makes the shape of the bubbles more nearly perfectly spherical.

[0026] Reservoir **22** contains fusionable material **24**. Preferably, fusionable material **24** is maintained in gaseous form and comprises one or more isotopes of light elements, such as deuterium, tritium, ^{3}He or some combination thereof. It is expected that the best results can be achieved where fusionable material **24** comprises a mixture of deuterium and tritium. For example, fusionable material **24** may comprise a 50/50 mixture of deuterium and tritium.

[0027] In operation, valve **26** is controlled to release gaseous bubbles **28** of fusionable material **24** into liquid **14** through aperture **15**.

Preferably, valve **26** is a pulsed valve, but valve **26** may comprise any suitable valve(s) including any of a wide variety of commercially available valves. Valve **26** is preferably controlled by controller **116**. Preferably, bubble **28** is spherical in shape and is released by valve **26** at the center of the bottom of vessel **12**. When released into liquid **14** at the bottom of vessel **12**, the buoyancy of bubble **28** causes it to rise toward the center of vessel **12**.

[0028] When a spherical bubble travels through a liquid, it may be distorted in shape by forces related to viscosity and/or fluid dynamics. Preferably, bubble **28** is relatively small when first released at the bottom of vessel **12** and bubble **28** remains small when it is travelling through liquid **14**. For example, the diameter of bubble **28** may be on the order of 100 μm. Because the size of bubble **28** is maintained relatively small during its movement through liquid **14**, the distortions introduced to the spherical shape of bubble **28** during its travel through liquid **14** may be reduced or minimized.

[0029] In reactor **10A** of Figure 1, pressure control system **16** rapidly reduces the pressure of liquid **14** at or near the time that bubble **28** reaches the center of vessel **12**. When the pressure of liquid **14** is reduced, the size of bubble **28** increases correspondingly. In the illustrated embodiment of the invention, pressure control system **16** rapidly reduces the pressure of liquid **14** by retracting piston **18**. The amount of pressure reduction and the amount of increase in size of bubble **28** may vary between embodiments of the invention. In one specific example embodiment, the pressure of liquid **14** is maintained at approximately 125 bar and bubble **28** is introduced into liquid **14** with a diameter of approximately 100 μm. When bubble **28** reaches the center of vessel **12**, the pressure is rapidly reduced to approximately 1 mbar,

resulting in a corresponding increase in the diameter of bubble **28** to approximately 5 mm.

[0030] At or near the time of the decrease in pressure of liquid **14** and the corresponding increase in size of bubble **28**, a high pressure, spherically symmetrical positive acoustic pulse **40** (see Figure 3) is introduced into liquid **14**. Acoustic pulse **40** may comprise a shock wave propagating in liquid **14**. As shown in Figure 3, acoustic pulse **40** converges on bubble **28**.

[0031] Preferably, acoustic pulse **40** is introduced soon after bubble **28** has increased in size (i.e. when bubble **28** is still located at or near the center of vessel **12**). The timing of acoustic pulse **40** is important. To obtain nuclear fusion, it is necessary to maintain a sufficiently high degree of spherical symmetry of bubble **28** as it is collapsed. If buoyant bubble **28** continues to travel through liquid **14** for a significant time after it has increased in size, there may be distortions to the shape of bubble **28**. If such distortions occur before bubble **28** is collapsed by acoustic pulse **40**, then they could interfere with the required symmetry.

[0032] In general, spherically symmetric acoustic pulse **40** may be introduced by a wide variety of apparatus. In reactor **10A** of Figure 1, pulse generation system **30** comprises a pneumatic-mechanical system made up of valve **42**, compressor **44** and a plurality of air guns **32**, each of which actuates a corresponding piston **36**. Air guns **32** and pistons **36** are positioned spherically symmetrically about the outside of spherical vessel **12**. Air guns **32** are loaded with compressed air (or other gas) which may be introduced by valve **42** and pressurized by compressor **44**. In reactor **10A**, air guns **32** are controlled by their respective latches **34**. When it is desired to create spherically symmetric acoustic pulse **40**, latches **34** are triggered (preferably by controller **116**), causing air guns

32 to accelerate pistons **36** to high speeds. Pistons **36** then strike outer surface **12A** of the wall of vessel **12**.

[0033] The time at which each individual piston **36** strikes outer surface **12A** of vessel **12** and the speed (i.e. kinetic energy) with which each individual piston **36** strikes outer surface **12A** of vessel **12** should be as close as possible to the same (i.e. within the minimum possible tolerances). Such consistent kinetic energy and timing ensures that acoustic pulse **40** produced in liquid **14** is spherically symmetric. In reactor **10A** of Figure 1, controller **116** controls the timing and the speed of pistons **36** by controlling the time at which latches **34** are triggered. In addition, the characteristics of air guns **32** may be fine tuned. Thus, after latches **34** are triggered, pistons **36** run "open loop" (i.e. without feedback).

[0034] The impact speed (i.e. kinetic energy) with which pistons **36** strike outer surface **12A** of vessel **12** is preferably made to be as high as practical without causing unacceptable damage to pistons **36** or vessel **12**. When pistons **36** impact vessel **12** with a higher impact speed, resultant acoustic pulse **40** has a higher peak pressure which results in a greater potential fusion yield. If the impact speed of pistons **36** can be made to be sufficiently high, high-pressure acoustic pulse **40** can become a shock wave.

[0035] When pistons **36** strike the outside of vessel **12**, spherically symmetric acoustic pulse **40** propagates through liquid **14**, and converges toward bubble **28**. Pistons **36** are preferably triggered at a time, such that when acoustic pulse **40** converges, it will converge at the point where bubble **28** will be located.

[0036] Figure 3 schematically depicts a pressure profile of the propagation of acoustic pulse **40** along the radial dimension of vessel **12** at various different points in time (**A** through **I**). At time **A**, bubble **28** is close to the center of vessel **12** and pulse generation system **30** triggers latches **34** to release pistons **36**. In between times **A** and **B**, pistons **36** strike outer surface **12A** of vessel **12** and generate spherically symmetric acoustic pulse **40**.

[0037] In general, the amplitude of a spherically converging waveform increases as 1/R where R is the instantaneous radius of the wave. As shown in Figure 3 at times **B**, **C** and **D**, the amplitude of spherically converging, spherically symmetric acoustic pulse **40** grows as 1/R. When spherically symmetric acoustic pulse **40** reaches bubble **28** (i.e at time **E**), its amplitude is given by:

$$P_{peak} \propto P_o\left(\frac{R_v}{R_b}\right) \tag{1}$$

where P_o is the initial pressure at the interior wall of vessel **12**, R_b is the radius of bubble **28** and R_v is the radius of vessel **12**.

[0038] In practice, the peak pressure of acoustic pulse **40** is limited by the precision and symmetry of vessel **12**, bubble **28** and acoustic pulse **40**. In addition, the initial pressure P_o cannot be made arbitrarily high, because increasing the kinetic energy with which pistons **36** strike vessel **12** will cause damage to vessel **12**, pistons **36** or both. Typically, high strength steel can handle impact pressures on the order of 10 kbar without incurring substantial structural damage. By way of example, if the symmetry of vessel **12**, bubble **28** and acoustic pulse **40** are within tolerances of approximately 3%, then the ratio R_v/R_b may be around 30. Assuming that P_o is approximately 10 kbar, then the peak pressure of

acoustic pulse **40** at the surface of bubble **28** (i.e. time **E** of Figure 3) will be approximately $P_{peak} = 300$ kbar. If the symmetry of vessel **12**, bubble **28** and acoustic pulse **40** are within tolerances of approximately 1%, then the peak pressure of acoustic pulse **40** at the surface of bubble **28** will be approximately $P_{peak} = 1$ Mbar. These examples illustrate the importance of symmetry to reactors according to the invention.

[0039] Acoustic pulse **40** produced by pulse generation system **30** of reactor **10A** is a positive waveform that is focused at the center of spherical vessel **12**. With good symmetry, the peak pressure of acoustic pulse **40** at the surface of bubble **28** may be 100 times (or more) greater than the pressure that could be withstood by the walls of vessel **12**. The peak pressure of acoustic pulse **40** represents a significant improvement over the peak pressure attainable using sinusoidal or otherwise oscillating continuous acoustic waves. As discussed above the maximum pressure that such waves can produce is limited to roughly twice the hydrostatic pressure. The hydrostatic pressure is limited to the pressure that can be withstood safely by the walls of vessel **12**.

[0040] When acoustic pulse **40** converges on bubble **28**, the peak pressure of pulse **40** is sufficient to cause bubble **28** to undergo a violent collapse. When this collapse occurs, the fusionable material **24** contained in bubble **28** is adiabatically compressed and heated to pressures and temperatures high enough to induce thermonuclear fusion in fusionable material **24**.

[0041] When fusion reactions occur, energy is released. This energy is captured by liquid **14** in the form of heat. The amount of heat absorbed by liquid **14** depends on the nature of the fusion reaction that occurs. Preferably, any neutrons produced in the fusion reactions are absorbed in liquid **14** and do not reach the walls of vessel **12**. This

absorption of neutrons in liquid **14** may prevent neutron activation and degradation of vessel **12** and the other reactor components. The heat energy absorbed by liquid **14** may be extracted from liquid **14** using various energy conversion techniques that are well known in the art of energy production. Liquid **14** preferably comprises a material which acts as a moderator to slow neutrons having energies in the range of 14 MeV to thermal energies.

[0042] Figure 2 depicts a fusion reactor **10B** according to a second embodiment of the invention. Reactor **10B** of Figure 2 is similar to reactor **10A** of Figure 1, in that it comprises a spherical vessel **12** filled with liquid **14**. However, reactor **10B** of Figure 2, comprises a fluid flow circuit **50**. Fluid flow circuit **50** comprises an input port **52**, through which fluid **14** flows into vessel **12**, an output port **54**, through which fluid **14** flows out of vessel **12**, and a pump **56** for directing the flow of fluid **14**. Fluid flow circuit **50** preferably comprises a flow control valve (not shown) and is controlled by controller **116**.

[0043] Reservoir **22**, which contains fusionable material **24** (preferably in gaseous form), is in communication with fluid flow circuit **50**. A controllable valve (not shown) may be provided at the junction between reservoir **22** and fluid flow circuit **50**. As with reactor **10A** of Figure 1, fusionable material **24** preferably comprises one or more light element isotopes, such as deuterium, tritium, ^{3}He or some combination thereof.

[0044] When desired, a bubble **28** of fusionable material **24** is released from reservoir **22** and flows through input port **52** into vessel **12**. The flow of liquid **14** through vessel **12** from input port **52** to output port **54** carries bubbles **28** relatively rapidly to the center of vessel **12**. In

some embodiments, the pressure of liquid **14** in reactor **10B** is not changed and there is no corresponding change in the size of bubble **28**.

[0045] Where liquid **14** is flowing inside vessel **12**, bubbles **28** containing fusionable materials **24** are preferably encapsulated in spherical capsules (i.e. micro-balloons). Such micro-balloons may be rigid to minimize any deformations to bubbles **28**. The walls of the micro-balloons may be fabricated, for example, from glass, plastic or other suitable materials. Micro-balloons of this type are used, for example, in inertial confinement experiments. The micro-balloons may be injected into the liquid **14** which enters vessel **12** at port **52**.

[0046] At or near the time that bubble **28** reaches the center of vessel **12**, a spherically symmetric positive acoustic pulse **40** (see Figure 3) is introduced into liquid **14**. As with reactor **10A**, spherically symmetric acoustic pulse **40** may be introduced by a wide variety of apparatus. In the illustrated reactor **10B** of Figure 2, acoustic pulse **40** is generated by pulse generation system **70** which includes impactors which strike outer surface **12A** of vessel **12**.

[0047] Pulse generation system **70** contains the same basic components as the pulse generation system **30** of reactor **10A**. Such components include: valve **42**, compressor **44**, a plurality of air guns **32**, and a corresponding plurality of pistons **36** positioned spherically symmetrically about the outside of spherical vessel **12**. As described further below, the times at which air guns **32** are fired, the kinetic energies with which pistons **36** impact vessel **12** and times at which pistons **36** impact vessel **12** may be controlled to cause acoustic pulse **40** to converge at the location of bubble **28**, even if bubble **28** is not perfectly centered with vessel **12**.

[0048] The pulse generation system **70** of reactor **10B** comprises a piston control system **71** associated with each of its pistons **36** (see Figure 4). As shown in Figure 4, each piston control system **71** includes a position feedback mechanism **72** and a servo loop **74**. Servo loops **74** may be digital and may be connected to controller **116**.

[0049] Each piston control system **71** uses its associated servo loop **74** and position feedback mechanism **72** to control the movement of its corresponding piston **36**. More specifically, piston control systems **71** control the speed (i.e. kinetic energy) with which each of pistons **36** strikes outer surface **12A** of vessel **12** and the time at which each of pistons **36** strikes outer surface **12A** of vessel **12** to determine various characteristics of acoustic pulse **40**. Piston control systems **71** may control the amplitude of acoustic pulse **40** and/or the location at which acoustic pulse **40** will converge. In preferred embodiments, acoustic pulse **40** is as large as possible without causing excessive damage to pistons **36** or vessel **12** and will converge on a bubble **28** that is located at or near the center of vessel **12**.

[0050] In the embodiment of Figure 4, each position feedback mechanism **72** comprises an optical fiber interferometer **76**, which measures the position of its associated piston **36**. Preferably, the position measurement accuracy of optical fiber interferometer **76** is greater than 1 μm. Other types of position sensors, such as acoustic, optical and/or capacitive position sensors could be used to implement position feedback mechanism **72**.

[0051] In the illustrated embodiment of Figure 4, each piston **36** comprises a permanent magnet **78** and each associated air gun **32** is surrounded by a coil **80**. Coil **80** is schematically depicted in Figure 4 as having a plurality of loops **80A-80G**. Those skilled in the art will

appreciate that coil **80** may have a different number of loops. Each one of a plurality of fast transistors **82A-82G** is associated with a corresponding one of loops **80A-80G**. The fast transistor **82A-82G** associated with each loop **80A-80G** is configured to limit and thereby control the amount of current that is allowed to pass through its corresponding loop **80A-80G**. The motion of piston **36** causes magnet **78** to pass through coil **80** and to induce current flow in each loop **80A-80G**. Current flowing in loops **80A-80G** of coil **80** generates magnetic fields which interact with the magnetic fields of magnet **78**. The energy necessary to provide current in each loop **80A-80G** comes from the kinetic energy of piston **36**. Accordingly, fast transistors **82A-82G** may be controlled by servo loop **74** to rapidly adjust the current which may be induced in loops **80A-80G** and to correspondingly control the movement of piston **36**.

[0052] The servo loop **74** of each piston control system **71** controls the movement of its corresponding piston **36** based, at least in part, on position information obtained from its associated position feedback mechanism **72** (i.e. optical fiber interferometer **76**). For example, if it was desired to have an acoustic pulse **40** (see Figure 3) converge precisely at the center of vessel **12** (i.e. if bubble **28** was going to be located at the center of vessel **12** when acoustic pulse **40** converges), then each servo loop **74** would control the movement of its corresponding piston **36**, such that each of the plurality of spherically symmetric pistons **36** strikes outer surface **12A** of vessel **12** with precisely the same speed (i.e. kinetic energy) at precisely the same time.

[0053] When pistons **36** strike outer surface **12A** of vessel **12**, they generate spherically symmetric acoustic pulse **40**. The propagation of acoustic pulse **40** in reactor **10B** is substantially similar to that in reactor **10A** and is shown schematically in Figure 3. Because pulse generation

piston **36** strikes vessel **12** may be controlled to adjust the location at which acoustic pulse **40** will converge. For example, if bubble tracking system **110** predicts that bubble **28** was going to be located some distance away from the center of vessel **12** at the time that acoustic pulse **40** would converge, then piston control systems **71** may control the movement of their corresponding pistons **36**, such that pistons **36** located at different positions around vessel **12** strike outer surface **12A** of vessel **12** at different times. In this manner, the location at which pulse **40** converges may be moved away from the center of vessel **12** toward a predicted location of bubble **28**.

[0056] Reactor **10B** may also comprise a bubble positioning system **118** (see Figure 5) which controls the position of bubble **28** and directs bubble **28** toward the center of vessel **12**. Bubble positioning system **118** may comprise a first pair of jets **120A**, **120B** located on opposing sides of vessel **12** along a first axis **122** and a second pair of jets **124A**, **124B** located on opposing sides of vessel **12** along a second spaced apart axis **126**. Each of first axis **122** and second axis **126** are preferably mutually orthogonal to one another and to the axis defined by input port **52** and output port **54**. For the sake of clarity in the illustration of Figure 5, second axis **126**, which is orthogonal to the page, and jet **124B** are not explicitly shown.

[0057] Jets **120**, **124** may cause flow of liquid **14** inwardly from the walls of vessel **12** along their respective axes **122**, **126**. Individual jets **120**, **124** may be controlled by controller **116**. Preferably, controller **116** is connected to receive measured position information relating to bubble **28** from bubble tracking system **110** and, based at least in part on the measured position of bubble **28**, to determine a flow required from each of jets **120**, **124** to move bubble **28** toward the

center of vessel **12**. As shown in Figure 5, controller **116** may also provide the actuation signals for jets **120**, **124**.

[0058] When acoustic pulse **40** converges on bubble **28**, the peak pressure of pulse **40** is sufficient to cause bubble **28** to undergo a violent collapse. When this collapse occurs, the fusionable material **24** contained in bubble **28** is adiabatically compressed and heated to pressures and temperatures sufficient to cause fusionable material **24** to undergo a thermonuclear fusion reaction.

[0059] When fusion reactions occur, energy is released. This energy is captured by liquid **14**. This heats liquid **14**. The amount of heat absorbed by liquid **14** depends on the nature of the fusion reaction that occurs. In the embodiment of Figure 2, reactor **10B** comprises an optional heat exchanger **90** which extracts heat energy from liquid **14**. Any suitable heat exchanger may be used. Heat exchangers are well known in the art of energy production. Pump **56** of fluid flow circuit **50** causes liquid **14** to flow out of vessel **12** through output port **54**, which leads to conduit **96** in heat exchanger **90**. As heated liquid **14** flows through conduit **96**, the heat from liquid **14** boils water **94**, turning water **94** into pressurized steam **92**. In turn, pressurized steam **92** turns turbine **98** and electric alternator **100**, converting the heat energy into electrical energy. After conversion of the heat energy into electrical energy, condenser **102** completes the thermal cycle of steam **92** back into water **94**. In the illustrated embodiment, turbine **98** also drives compressor **44** of pulse generation system **70**.

[0060] Heat exchanger **90** is not required in all embodiments of the invention. In some embodiments, heat energy produced in liquid **14** may be used directly. Other forms of heat energy conversion equipment

may be used and may convert the heat to electrical energy or into other forms of energy.

[0061] In operation, bubbles **28** (which may be encased in micro-balloons) are released into liquid **14** contained in vessel **12**. Bubbles **28** may carried toward the center of vessel **12** by the flow created by fluid flow circuit **50**. During their travel towards the center of vessel **12**, the position of bubbles **28** may be tracked by bubble tracking system **110** and may be adjusted by bubble positioning system **118**. Pulse generation system **70** creates a positive spherically symmetric acoustic pulse **40** by striking outer surface **12A** of vessel **12** at a plurality of spherically symmetric locations. Pulse generation system **70** may create pulse **40** using a plurality of pistons **36** actuated by air guns **32**. The kinetic energy and timing of each piston **36** may be controlled by a piston control system **71** which may use information from the bubble tracking system to control characteristics of pulse **40**, such as the location of convergence of pulse **40**. Acoustic pulse **40** converges on bubble **28**, compressing and heating the fusionable material contained therein to thermonuclear pressures and temperatures sufficient to promote fusion reactions. The fusion reactions release heat energy which is captured in liquid **14** and which may be converted to electrical energy (or other forms of energy) by heat exchanger **90**.

[0062] As will be apparent to those skilled in the art in the light of the foregoing disclosure, many alterations and modifications are possible in the practice of this invention without departing from the spirit or scope thereof. For example:

- Those skilled in the art will appreciate that elements of reactor **10A** (Figure 1) may be combined with elements of reactor **10B** (Figure 2). For example, piston control systems **71** may be incorporated into pulse generation system **30** of reactor **10A** to

control and minimize any differences in the speed and timing of pistons **36**. In other examples, fluid flow system **50** and or the heat exchanger **90** of reactor **10B** may be introduced into reactor **10A**.

- The spherical vessels **12** of reactors incorporating the concepts of the invention may generally be of any size. As discussed above, the currently preferred vessel **12** is approximately 1m in diameter. If vessel **12** is made larger, then the peak pressure of acoustic pulse **40** may be higher (see equation 1). However, if vessel **12** is made larger, then it may be more difficult to control the symmetry of the vessel itself, it may be more difficult to control the timing, velocity and symmetry of the associated pulse generation systems. These trade-offs related to the size of vessel **12** are a matter of engineering and the size of vessel **12** may be selected to achieve a desired result.
- Reactors incorporating the concepts of the invention and, in particular pulse generation systems **30**, **70**, may be designed to recapture some of the energy expended to create acoustic pulse **40**. After bubble **28** collapses (see Figure 3E), waveform **40** continues to propagate and diverges radially towards the inner wall of vessel **12** as shown in Figures 3F, 3G and 3H. When diverging waveform **40** reaches the inner surface of the wall of vessel **12**, it may accelerate pistons **36** radially outwardly and thereby recompress the air (or other gas) in air guns **32**. This recompression of air guns **32** may help to improve the efficiency of reactors incorporating the invention by minimizing the energy expenditure to produce subsequent acoustic pulses **40**. Typically, some energy will be lost as acoustic pulse **40** propagates through vessel **12**. As such, an acoustic pulse **40** will not supply all of the energy required to reset air guns **32** to supply another acoustic pulse **40**. The air (or other gas) in air guns **32** may be

replenished to the desired level by compressor **44** and valve **42** which may be controlled by controller **116**.

- The pulse generation systems **30, 70** described above incorporate a plurality of impactors that are spherically symmetrically distributed about the outside of vessel **12**. In the illustrated embodiments, the impactors comprise pistons **36**. The exact number of pistons **36** may vary. Pulse generation systems **30, 70** may comprise over 50 pistons **36** and preferably comprises over 100 pistons **36**. As described above, each piston **36** also has a corresponding air gun **32**. The mass and speed of pistons **36** depends on the number of pistons and the total amount of kinetic energy required from the pulse generation system **30, 70**. For example, a pulse generation system comprising 100 pistons, each of which weighs 0.5 kg and travels at 200 m/s when impacting vessel **12** can provide a total of 1 MJ of kinetic energy.
- Pulse generation systems **30, 70** may be implemented by a variety of other techniques which generate spherically symmetric high-pressure acoustic pulses. For example, pulse generation systems **30, 70** may be implemented using electrical components, such as electrical actuators, electrical energy storage and/or electrical switches. Similarly, pulse generation systems **30, 70** may be implemented using chemical energy components, such as components based on exploding energetic compounds.
- The rate at which energy is produced in fusion reactors incorporating the concepts of the invention depends on the period of time required to move successive bubbles **28** to the center of vessel **12** and to apply successive acoustic pulses **40** to collapse bubbles **28**. This period may vary significantly, depending on the buoyancy of bubble **28** (reactor **10A**), the flow rate of fluid flow circuit **50** (reactor **10B**), and the speed of acoustic waves in liquid **14**. It is expected that reactors incorporating the concepts of the

invention may be designed to be pulsed at rates of over 2 Hz and, preferably, at rates of 4 Hz or higher.

- The rate of fluid flow through circuit **50** of reactor **10B** depends on a number of factors, including the rate of heat energy production in reactor **10B** and the upper limit of the speed at which bubble **28** may be transported through liquid **14** without distorting the spherical shape of bubble **28**. A stable flow pattern is preferably maintained. In a preferred embodiment, a toroidal flow pattern is maintained, wherein liquid **14** rises along a central axis of reactor **10B** and travels downwardly around the circumference of reactor **10B**. Under such a toroidal flow pattern, the currently preferred flow rate of fluid flow circuit **50** is approximately 0.25 m^3/s for a vessel **12** having a 1m diameter and a pulse rate of 4 Hz. As more heat energy is produced, the flow rate of circuit **50** may be increased to extract the heat energy from liquid **14** in heat exchanger **90**. However, the flow rate of circuit **50** may not be increased indefinitely, because higher flow rates tend to distort the shape of bubbles **28**, reducing the fusion yield.
- When the fusion reaction produces a fast neutron and liquid **14** is lithium, then there is a possibility that the liquid lithium will react with the fast neutron to produce tritium ($^6Li + n => T + {}^4He$ 4.6MeV). This tritium may be extracted and re-used by the system as fuel (i.e. fusionable material **24**).
- As shown in Figure 2, compressor **44** may use some of the energy produced by reactor **10B** to replace the air (or other gas) in the air guns **32** of pulse generation system **70**. Compressor **44** may be driven by turbine **98**. In alternative embodiments, the pressurized steam **92** produced in heat exchanger **90** may be used directly to power air guns **32** of pulse generation system **70**.
- Bubble tracking system **110** may comprise a larger number of position detectors to improve the accuracy of the measured

position of bubble **28**. Bubble tracking system **110** of Figure 5 may include more than three ultrasonic position detectors **112**.

- Bubble positioning system **118** may comprise more than two pairs of jets **120**, **124**. Those skilled in the art will appreciate that additional jets (not shown) may be used to improve the accuracy with which bubble positioning system **118** may position bubble **28**.

[0063] Accordingly, the scope of the invention is to be construed in accordance with the substance defined by the following claims.